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BACKGROUND OF THE COMPLETED RESEARCH; RELEVANCE TO SOLAR PHYSICS

The primary objective of our research remains the study of the atomic structure of highly stripped heavy ions, and their modes of formation and destruction in collisions. Because many relatively forbidden de-excitation processes involving excited states of these ions are driven at higher rates than in their low Z counterparts by increased magnetic interactions, it becomes possible to study the rates of these processes to an accuracy which is competitive with theoretical structure calculations. Some of the ions which we study (e.g. highly ionized O, F, S ions) are abundant, metastable constituents of the solar corona and of laboratory and atmospheric plasmas of similar temperature. Metastable systems containing just a few electrons have been our main interest, since their forbidden decays relate most closely to fundamental atomic structure theory. Since many of the forbidden lines we study have been observed in the solar chromosphere, transition region and corona, and are used as tools for their study, our experiments frequently contribute something of interest to solar physics.

In March, 1972, NASA provided a one-year grant (NGR-43-001-114) for some initial ion beam experiments related to the physics of the solar corona. We review our results under this in this

in this report, topic by topic. Additional information is available in our semi-annual status report, dated October, 1972, and in our renewal proposal entitled "Highly Ionized Nickel, Chlorine, and Sulfur: Line Identification and Lifetime Measurements in the XUV and Soft X-Ray Regions."

Publications resulting from NASA Grant support, 1 March 1972-31 August 1973: Articles in Major Journals and Proceedings (in inverse chronological order):

1. "Experimental Projectile Charge Dependence of ArK and NeK X-Ray Production by Fast, Highly Ionized Argon Beams in Thin Neon Targets," Phys. Rev. Lett. 30, 1289 (1973).
2. "Experimental Projectile Charge Dependence of ArK and NeK X-Ray Production by Fast, Highly Ionized Argon Beams in Neon Targets," Proceedings, Eighth International Conference on the Physics of Electronic and Atomic Collisions, B. Cobic and M. Kurepa, editors, Graficko Preduzece Buducnost, Zreajanin, Yugoslavia (July, 1973), p. 727.
3. "Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," Phys. Rev. A8, 145 (1973).
4. "Projectile Structure Effects on Neon K X-Ray Production by Fast, Highly Ionized Argon Beams," Phys. Rev. Lett. 29, 1577 (1972).

5. "Metastable States of Highly Excited Heavy Ions," in Atomic Physics, Vol. 3, Plenum Press, London (1973), p. 327.
6. "Projectile Charge State Dependence of K X-Ray Production by 1-4 MeV/amu Heavy Ions in Gases," submitted for publication to Phys. Rev. A.

Other papers (in inverse chronological order):

7. "Observation of Coherently Excited Dipole Charge Distribution Oscillations in Collision-Averaged Foil Excitation of the $n=2$ H Levels," to be published in Bull. Am. Phys. Soc., November, 1973.
8. "Effective Charge State of Heavy Ions Penetrating Solids Deduced from Comparing X-Ray Yields in Gases and Solids," to be published in Bull. Am. Phys. Soc., November, 1973; and to be presented at the Third International Conference on Atomic Collisions in Solids, Gatlinburg, Tennessee, September, 1973.
9. "Projectile Structure Effects in Heavy-Ion Induced X-Rays: Projectile X-Rays," to be published in Bull. Am. Phys. Soc., November, 1973.
10. "Projectile Structure Effects in Heavy-Ion Induced X-Rays: Target X-Rays," to be published in Bull. Am. Phys. Soc., November, 1973.
11. "Mean Life of the Metastable 2^3P_1 State of the Two-Electron Fluorine Ion," Bull. Am. Phys. Soc. 11, 610 (1973).

Technical Discussion of Research Results Listed

Metastable State Lifetimes of Highly Stripped Ions. By measuring the radiative decay in flight of a foil-excited helium-like fluorine beam, we determined the lifetime of the metastable 2^3P_1 state of the two-electron ion F^{7+} , and published the resulting publications 3 and 11. Our data yield the singlet-triplet intercombination transition probability

$$A(1^1S - 2^3P_1) = (1.77 \pm 0.10) \times 10^3 \text{ sec}^{-1},$$

which is in excellent agreement with theoretical calculations of a strongly Z -dependent spin-orbit-induced electric dipole decay, and extends our earlier measurements for ions in this isoelectronic sequence. Because this transition is observed in the solar spectrum for all abundant heliumlike ions from carbon to iron, this measurement is relevant to solar physics.

The $1^1S_0 - 2^3P_1$ intercombination transition in the two-electron atomic system is accompanied by a change in the atomic spin angular momentum. In the nonrelativistic limit such a decay cannot proceed by electric dipole (E1) radiation because of the $\Delta S=0$ selection rule. The parity change that occurs when the atomic state changes from P to S, together with the $\Delta S=0$ selection rule,

makes magnetic dipole ($M1$) decay doubly forbidden. Nevertheless, this intercombination line has been known ever since it was first observed by Lyman in neutral helium almost 50 years ago. Although the wavelength of this $592\text{-}\overset{\circ}{\text{A}}$ (He I) line has been measured to high precision, its small branching ratio has, until recently, precluded a measurement of the $1^1S_0 - 2^3P_1$ decay probability.

The observation of heliumlike intercombination lines in the emission spectra of highly stripped ions in both laboratory plasmas and solar corona stimulated attempts to compute the associated decay rates. It was found that singlet-triplet mixing by the (relativistic) spin-orbit interaction allows the 2^3P_1 state to decay to the ground state by E1 emission. Our subsequent measurements of the $1^1S_0 - 2^3P_1$ transition probability in two-electron nitrogen and oxygen ions were consistent with the theoretical estimates. In publications 3 and 11 an extension of this work along the isoelectronic sequence to $Z=9$ was reported. The Z dependence of the transition probability is so strong that a change of Z of only one unit ($Z=8$ to $Z=9$) is accompanied by more than a threefold increase in the decay rate. The results of the present experiment are in good agreement with theoretical predictions.

Subtraction of the known $2^3S_1 - 2^3P_1$ transition probability¹⁰ $0.0915 \times 10^9 \text{ sec}^{-1}$ from our experimental value for $\tau^{-1} = (1.87 \pm 0.10) \times 10^9 \text{ sec}^{-1}$ gives an experimental result for the spin-orbit-induced E1 transition probability

$$A(1^1S_0 - 2^3P_1) = (1.77 \pm 0.10) \times 10^9 \text{ sec}^{-1},$$

which agrees with the variational result $1.85 \times 10^9 \text{ sec}^{-1}$ of Drake and Dalgarno¹ and the semi-empirical result $(1.7 \pm 0.2) \times 10^9 \text{ sec}^{-1}$ of Elton.² About 8% of the variational result is due to mixing of 2^3P_1 with singlet states of $n > 2$.

The intercombination transition discussed here is observed in the solar spectrum of all abundant elements between carbon and iron.³ The intensity of this transition relative to that of $1^1S_0 - 2^3S_1$ M1 transition is used in the determination of the electron density in solar active regions.⁴ According to Jordan³ the precise value of $A(1^1S_0 - 2^3P_1)$ is important for this density determination only up to about $Z=10$. As discussed above, the $2^3S_1 - 2^3P_1$ transition is the dominant radiative decay for $Z < 6$. The present measurement at $Z=9$ therefore falls within the most critical region $7 < Z < 10$.

We have also measured the $1^1S_0 - 2^3P_2$ transition probability in a helium-like ion (Ar XVII) and have a result which agrees both with theory and an earlier experiment⁵ to within overlapping error bars, and in fact comes somewhat closer to theory than did this earlier experiment. When combined with our measurement of the $1^1S_0 - 2^3P_1$ lifetime in O VII, these two key lifetimes in the theory of Gabriel and Jordan concerning the use of the intercombination and forbidden helium-like line intensities (as in O VII) to determine electron densities in solar active regions can be said to be experimentally verified.

In related work, we have studied the autoionization electron emission lifetimes of various excited heavy ions, including the so-called non-radiative $(1s2s2p)^4P$ state of lithiumlike three-electron ions like OVI and Ar XVI. These results were selected for presentation at the Third International Conference on Atomic Physics and have appeared in the Plenum Press volume concerning the conference (publication 5). Our data deviate increasingly with Z from a semi-empirical scaling rule of Levitt et al. (Phys. Rev. A3, 130 (1971)). It was recently pointed out to us by L. Cocke (Kansas State University) that a significant part of this departure is due to the opening of a magnetic quadrupole ($M2$) radiative decay channel to $1s\ 2s$. Hence the term non-radiative is quite misleading. It would seem that astrophysical theorists have missed this point, and that interpretation of solar spectra in regions where the so-called non-radiative autoionizing states in fact radiate at rates characteristic of better known forbidden decays may be required.

Metastable State Quenching Measurements

As already noted, our attempts to measure the $1^1S_0 - 2^3P_2$ transition probability in a helium-like ion (Ar XVII) agreed both with theory and an earlier experiment (Marrus and Schmieder) to within overlapping error bars, and in fact came somewhat closer to theory than did this earlier experiment. When combined with

our measurements of the $1^1S_0 - 2^3P_1$ lifetime in O VII and F VIII, these two key lifetimes in the theory of Gabriel and Jordan concerning the use of the intercombination and forbidden helium-like line intensities to determine electron densities in solar active regions can be said to be experimentally verified. Our attempts to measure the collisional excitation rate $C(2^3S - 2^3P)$ (needed in the Gabriel-Jordan theory) have been complicated by competition from processes like $C(1^1S - 2^1,^3P)$. Even though the latter collision rates are orders of magnitude less than $C(2^3S - 2^3P)$, it turns out that the 1^1S state population outweighs the 2^3S population by a similar ratio, so that the population-rate products NC are comparable. Also, it appears from the data that for H_2 target gas, target protons cause $2^3S - 2^3P$ transitions at a rate comparable to $C(2^3S - 2^3P)$. Hence we have been able to set an upper limit to $C(2^3S - 2^3P)$ which is a few times the calculated rate, but not the rate itself. By using a variety of target gases (H_2 , He, Ne, Ar), however, we have been able to devise and test an approximate scaling rule for separating the contributions of target electrons and heavy target particles of such rates. If n is the number of target electrons per heavy target particle whose internal atomic velocity is less than that of the ionic projectiles in such beam experiments then the rates for the

various excitation and ionization processes we have observed (like $2\ ^3S - 2\ ^3P$) scale approximately as $n + (Z - n)^2$. The heavy target particle contribution goes as $(Z - n)^2$, and the target electron contribution goes as n . For our fast, heavy projectiles in H_2 gas, then, $n \sim 1$ and the target electron and proton contributions are about equal.

When Ne was used as the target gas, we discovered a very strong production of Ne K x-rays by fast argon ion impact. This discovery led to a completely new and unexpected line of investigation, as discussed in the next section.

Exponential Exchange State Dependence of X-ray Production Cross-sections. Publications numbered 1, 2, 4, 6, 8, 9, and 10 deal with the discovery and exploration of strong incident ion charge state effects on heavy ion inner-shell vacancy production, which gives rise to both projectile and target x-ray emission.

The production of K-shell vacancies in heavy-target atoms (nuclear charge Z_T) during collisions with light charged particles (nuclear charge Z_p) is well understood as a Coulomb ionization process. Both a plane-wave Born-approximation model and a classical, binary-collision model yield universal curves which fit existing data reasonably well so long as the structure of

the bombarding projectile can be ignored. The projectile is assumed to be either a fully stripped ion, or an ion or atom whose electrons are loosely bound compared to the binding of the target K electrons, i.e., $Z_P \ll Z_T$.

The structure of the projectile becomes important when its nuclear charge is comparable to that of the target. For suitable projectile energies, a quasimolecule is formed during deeply penetrating collisions; under the appropriate circumstances, greatly enhanced K x-ray yields can be observed in the lighter collision partner, especially when energy-level matching occurs. These large yields are often due to a transfer of a K-shell electron in the lighter collision partner to an unoccupied level in a shell of higher principal quantum number (often the L shell) in the heavier collision partner. This electron promotion concept has had remarkable success in providing qualitative understanding of many collision phenomena in both symmetric and asymmetric collisions. It is usually assumed that the velocity of the bombarding projectile is small compared with the velocity of a K-shell electron in the target atom ($v_P \ll Z_T \alpha c$, where α is the fine-structure constant and c the speed of light) so that a molecular aggregate may exist for an appreciable time.

What is different about the new experiments is the discovery

that there is a third, high velocity regime, described neither by existing Coulomb ionization nor molecular orbital theories, which will require new theories to explain both the cross section size and the strong dependence on the ionic charge of the projectile, as distinct from the nuclear charge, the only parameter entering into Coulomb ionization theories. The large body of data on argon + anything collisions does not extend to the high-energy or high-charge states considered here. Our experimental systems fall outside the scope of the plane-wave Born approximation because $Z_p > Z_T$, and because the projectile contains tightly bound electrons. The experiments probe the electron promotion model in the region $v_p \sim Z_T \alpha c$, where there is strong doubt about its validity. We find that the K x-ray yield is strongly dependent upon the charge state of the projectile.

In publication 4 we reported the observation of neon K x-ray yields which were strongly dependent upon the charge state of incident highly stripped argon ions. The target x-ray yield increased by a factor of ~ 10 when a thin foil was placed just upstream from the target; thereby changing the projectile charge from +6 to an average value of +14. The new developments described in 1,2 are the discovery of significantly larger projectile charge-state-dependent K x-ray yields than previously encountered, the observation of an even larger effect on the projectile yield than on the target yield, and a systematic test of the energy-level-matching hypothesis at relatively high projectile velocity.

The binding energy of an electron that is excited into the normally empty 2p shell or Ar^{14+} is nearly equal to that of a 1s electron in the neutral neon atom. This near match of energy levels suggested the possibility of an enhanced cross section for electron transfer from the neon K shell to the empty Ar^{14+} L shell during deeply penetrating collisions. Such an electron promotion presumably cannot occur when the projectile is Ar^{6+} because in that case the L shell is full.

In order to investigate this level-matching hypothesis, we improved the experiment by interposing an analyzing magnet between stripping foil and gas cell which was capable of selecting, at 80 MeV, usable argon currents in single charge states +12 through +17 covering the range from carbonlike to hydrogenlike argon. The primary beam Ar^{6+} is also available when the foil is removed. The yield of both target and projectile K x rays is found to increase dramatically with projectile charge state throughout the region studied. An overall 60-fold (exponential) increase in neon K x-ray yield is observed together with more than a 1000-fold (>exponential) increase in the argon K x-ray yield when the argon charge is varied from +6 to +17. As far as is known, these are the largest projectile charge-state-dependent effects ever reported for K x-ray production. No particular enhancement occurs in the region where energy-level matching is expected to occur, which implies that level matching

is not an important criterion for this ionization process at this velocity. The new results demonstrate even more emphatically than before the need to incorporate detailed projectile structure into theories of inner-shell ionization.

A more comprehensive study in which other projectiles, targets, and energies were also used is reported in 6, just submitted for publication. Results were qualitatively very similar. The projectile-target combinations studied in these experiments were Ar^{q+} on Ne (at 80 and 152 MeV), Cl^{q+} on Ne and SF_6 (at 42 and 50 MeV), and F^{q+} on two chlorine-bearing Freon compounds (at 43 MeV).

These experiments raised the possibility of exploiting such charge state dependence for the purpose of shedding light on long-standing controversies on whether it makes sense to assign charge states to ions as they penetrate solid matter, and if so, what charge states to assign. Comparison of solid and gas target K x-ray production cross-sections for equal atom target thicknesses (atoms/cm^2) would yield data on the ion charge state inside the solid, since the gas cross-section charge state dependence is so steep. An initial attempt to do this is the subject of publication 8.

References

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